1. Air-Sea and Lateral Exchange Processes in East Indian Coastal Current off Sri Lanka
2. ASIRI: Remote Sensing of Atmospheric Waves and Instabilities (RAWI)

H.J.S. Fernando and I. Lozovatsky
University of Notre Dame
Department of Civil and Environmental Engineering and Earth Sciences,
Notre Dame, IN 46556
Tel: 574-631-9346 and 574-631-3052; Fax: 574-631-9236
e-mail: hfernand@nd.edu and ilozovat@nd.edu

Award Number 1: N00014-13-1-0199
Award Number 2: N00014-14-1-0279
www.nd.edu/~dynamics

LONG TERM GOALS

The long-term goal of our research program is to understand small to synoptic scale processes in the northern and equatorial Indian Oceans, with the goal of contributing to improved prediction of atmospheric and oceanic conditions (weather) of the Indian Ocean (IO) and beyond. Strong ocean-atmosphere coupling in the region calls for detailed observations on both sides of the sea surface, covering relevant scales and interactions. Capturing subseasonal variability of key signals carried by oceanic currents and atmospheric circulation and delineating their role in phenomena of significance will be of interest. Some examples include Madden Julian Oscillation, planetary waves, transients of Hadley circulation, Kelvin-Rossby wave packets in the atmosphere and the seasonally reversing current systems and upwelling patterns in the ocean, all of them are perceived to be coupled. It is hypothesized that smaller scale processes such as convection and turbulent entrainment, which have received scant attention hitherto, can play a key role in the dynamics of processes at larger scales, which needs to be delineated. Observations covering critical elements such as Bay of Bengal (BOB) circulation, East India (and Sri Lanka) current, internal and planetary wave propagation as well as capturing atmospheric convection and circulation in a swath of the equatorial IO are expected to contribute immensely to the understanding of regional weather and its global impacts. Collaboration on the conduct of regional atmosphere-ocean coupled models using a suite of platforms is also a goal.

OBJECTIVES

The objective of the first project is to understand subseasonal processes in the Northern BOB in the context of monsoonal dynamics, which include regional circulation and their space-time variability down to the scales of turbulence and mixing in the upper ocean that affect local air-sea fluxes. The project seeks to collect hydrographic data sets in the international waters using R/V Revelle (US) and in Sri Lankan coastal waters using R/V Samuddrika (Sri Lankan). The measurements include

Report Documentation Page			*Form Approved* *OMB No. 0704-0188*

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **30 SEP 2014**	2. REPORT TYPE	3. DATES COVERED **00-00-2014 to 00-00-2014**
4. TITLE AND SUBTITLE **1. Air-Sea and Lateral Exchange Processes in East Indian Coastal Current off Sri Lanka 2. ASIRI: Remote Sensing of Atmospheric Waves and Instabilities (RAWI)**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Notre Dame,Department of Civil and Environmental Engineering and Earth Sciences,Notre Dame,IN,46556**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

thermohaline stratification, surface eddies and warm water pools, currents and its vertical/horizontal structure and kinetic energy dissipation rate. This research is conducted under the Air-Sea Interactions of the Northern Indian Ocean (ASIRI) Project.

The atmosphere-ocean interaction in the IO occurs over a continuum of scales, from regional-scale heat transport by the Walker circulation down to local heat fluxes contributed by entrainment of warm air from aloft to the sub-cloud layer, which in turn affect local air-sea fluxes. Observations of atmospheric convection over western equatorial IO, MJO and associated phenomena such as propagating cloud clusters and turbulent entrainment from upper layers would be made. This research is in the realm of the ASIRI-RAWI and Northern Arabian Sea Circulation Autonomously Researched (NASCAR) Project.

Also expected from the first project is partnership with Sri Lankan scientists from the National Aquatic Resources Research Agency (NARA), who are conducting regular detailed transects across the East Indian Current segment along the Sri Lankan East coast (Sri Lanka Current), and with the Postgraduate Institute at the University of Peradeniya. In addition, the first project provides support for the US scientists conducting research in the area, supported by ONR 322PO. Close collaboration is also maintained with the Naval Research Laboratory's E-BOB Project (PI: Hemantha Wijesekera). In the second project, collaboration is sought with institutions in Seychelles and Singapore for atmospheric deployments. In all cases, the project expects to build capacity of local scientists through graduate student training and providing assistance in field work such as setting up and deployment of modern remote sensors such as drifters, gliders, and accessing global data sets (*e.g.*, ARGO floats).

APPROACH

Project 1: Conduct of microstructure and CTD measurements in the BOB onboard the R/V Roger Revelle and in Sri Lanka coastal waters using R/V Samuddrika. The latter is carried out along selected tracks of southern and eastern Sri Lanka, extending from near-shelf to deep-ocean within the Sri Lankan EEZ.

Project 2: Deployment of a suite of atmospheric instruments in the coasts of three IO island nations, Sri Lanka, Seychelles and Singapore to capture small-scale events pertinent to the propagation of westerly disturbances originating in the western equatorial IO. These deployments are conducted in collaboration with the Army Research Laboratories. A combination of Lidars, radiosonde launches, towers, radiometers and other remote sensors will be employed. In addition, the ocean response will be monitored using glider deployments as well as a Samuddrika transect between Colombo and Maldives.

The capacity building component includes participation of scientists from partnering countries in US-led field campaigns in the IO as well as training of graduate students at University of Notre Dame in analyzing oceanographic and atmospheric data. A group of technicians and engineers from the US will conduct hands-on training of partner-country technical personnel in setting up and operating state-of-the-art instruments.

WORK COMPLETED

A. The Sri Lankan collaboration led to a large number of oceanic transects with CTD, ADCP and Vertical Microstructure Profiler (VMP) measurments in the eastern Sri Lanka using the R/V Samuddrika (Chief Scientist: Mr. Priyantha Jinadasa, supported by the project). These cruises were

sometimes associated with the deployment of Gliders and PIES, in support of the activities of other ASIRI investigators.

B. Logistical and scientific plans for ASIRI-RAWI deployments at the end of January 2014 have been completed. The US collaborators include ARL and NOAA Earth System Research Laboratory, Boulder, CO, USA.

C. During the research cruise of R/V Roger Revelle in BOB (1st leg, November 2013), turbulence and background stratification were measured using a VMP. The profiler carries two airfoil probes (for kinetic energy dissipation rate ε), two fast thermistors (measuring microstructure gradients to estimate the temperature dissipation rate χ), three component accelerometer, pressure sensor (depth) and a Seabird CTD (SB) unit for precise measurements of temperature, salinity, and density. Because of a malfunction of the VMP winch, the deployment (down to ~ 120 – 140 m) and recovery of the instrument were done manually, with a characteristic "free falling" velocity in the range 0.65 -0.7 m/s.

During November 13-16, comprehensive testing of VMP were conducted under various stratifications and wind conditions, based on which several refinements were made to the sampling program. Starting from November 18, a high-quality dataset (55 profiles) were collected at 4 mini sections (blue, green, and red, November 18-21) and along a mesoscale transect (magenta, November 23) shown in Fig 1.

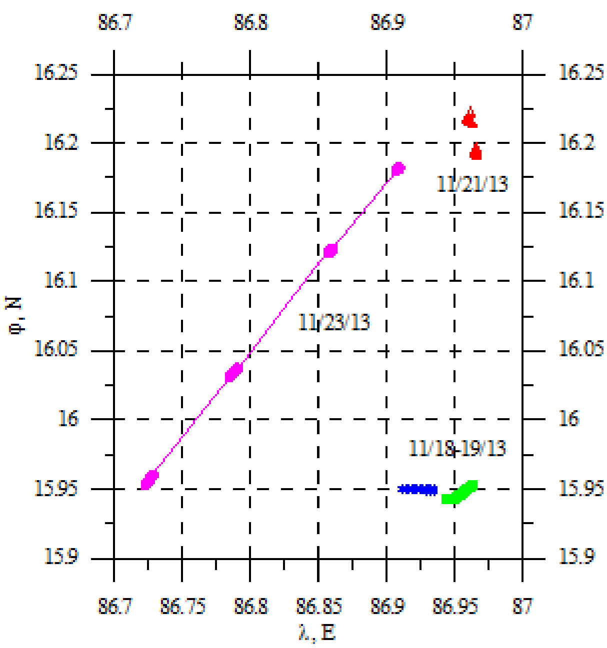

Figure 1. VMP measurements in the BoB during the 1st leg (Nov 11 - 27, 2013) of the R/V Roger Revelle cruise.

In this cruise, Notre Dame graduate student Kelly McEnerney participated in shipboard CTD and ADCP measurments, where curious low salinity cold water pools (LSCWP) were observed. The measurments taken through these pools were analyzed.

D. During the pilot cruise conducted in the Sri Lankan EEZ on February 3, 2014, nine VMP and SB casts were carried out in deep waters near the shelf break off Weligama (Fig. 2). This is the first ever VMP and SB profiles taken from Samuddrika, confirming its potential of profiling in blue waters under relatively calm winds (wind speed up to 6-8 m/s) and low swell. Useful data on the surface mixed-layer deepening in the southern branch of Sri Lanka current (SLC) during the winter season was obtained.

E. A 60 miles long longitudinal transect (11 stations 16 SB and 17 VMP casts) were taken across the Sri Lanka coast south off Weligama during the April cruise of R/V Samudhrika (Fig. 2b). In addition to this transect, 14 fast VMP profiles were obtained during a 3 hrs drift near the shelf break (Fig. 2b).

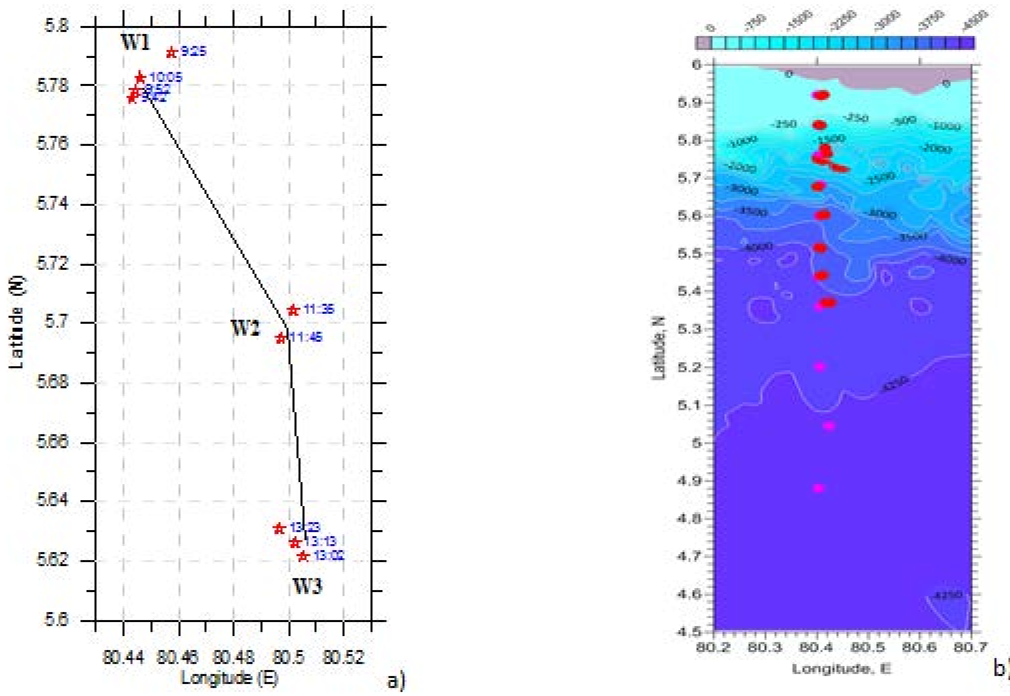

Figure 2. R/V Samuddrika measurements taken in February (a) and April (b) south off the Sri Lankan coast. Positions and time of the casts at stations W1-W3 are shown in a). The transect stations in b) are shown by circles; a drift station with 14 VMP casts near the shelf break are given by small stars.

F. In September, R/V Samuddrika completed a 60 miles latitudinal section along ~ 8 N (Fig. 3), covering 9 SB stations with 20 VMP profiles.

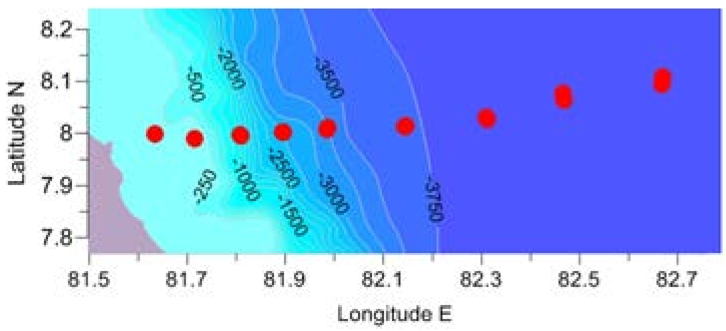

Figure 3. September section of R/V Samuddrika taken in the BoB off Trincomalee.

G. In July, the co-PI Lozovatsky and a Notre Dame PhD student Annunziata Pirro participated in the 2nd leg of the R/V Revelle cruise in the Southern BOB (Chief Scientist: Dr. H. Wijesekera). They helped deploy ScanFish and participated in a special 20-hr. experiment focused on internal-wave dynamics in the BOB pycnocline and small-scale dynamics of the surface layer.

H. WRF modeling was conducted for the second project, in preparation for the January 2015 deployment. The results were compared with routine monitoring stations available from the area. Some of the infrastructure necessary for the deployments are being developed in Sri Lanka. The nature of the deployments in Seychelles and Singapore do not require additional infrastructure needs.

I. Mr. Priyantha Jinadasa spent 5 months at University of Notre Dame (March-June, 2014) to conduct research on internal waves and turbulence in shallow waters. His PhD thesis is under examination by the Post-Graduate Institute of the University of Peradeniya, Sri Lanka.

RESULTS

A. Turbulence in the Northern BOB. Microstructure measurements in 16.95^{o} to 16.25^{o} N and 86.7° to 87.0° E (Fig.1), toward the east side of a possibly elongated cyclonic eddy with north or northwest-directed flow, revealed the following.

A1. Wind-induced mixing in the surface layer with weak interfacial mixing. Very strong density stratification below a thin (<15-20 m deep) mixed surface layer (SL), observed on Nov 18-19, damped the wind-induced turbulence almost completely, precluding penetration of turbulence below *z* ~ 20 - 25 m (Fig. 4a).

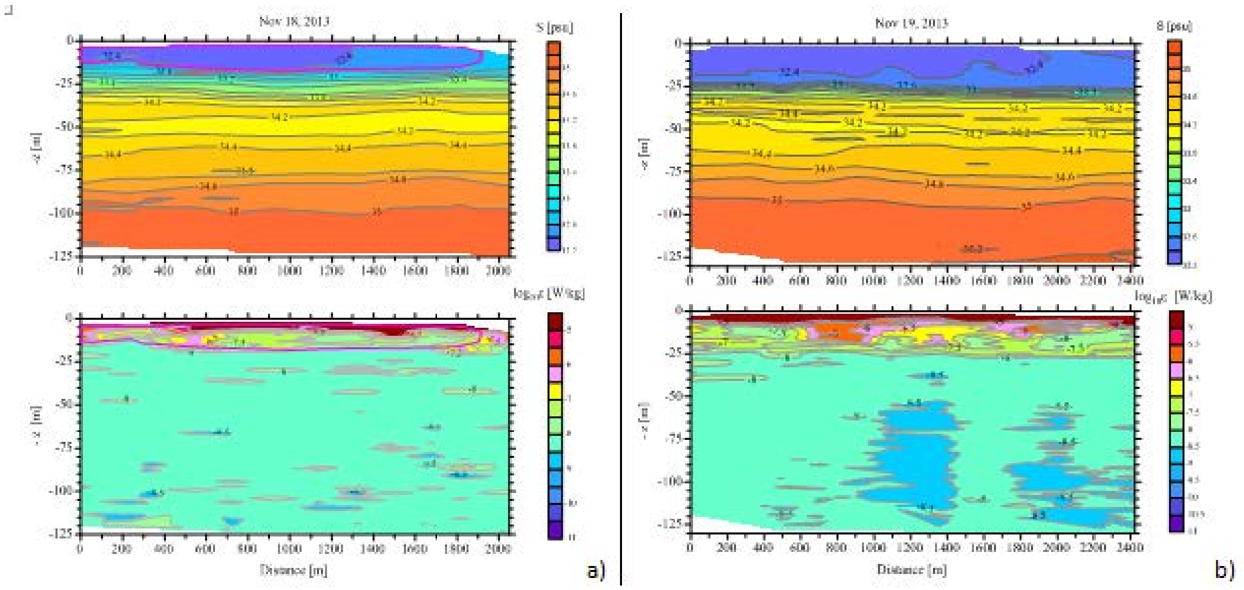

Figure 4. The salinity (upper panels) and dissipation rate (lower panels) taken in mini-sections of BOB on November 18 (a) and 19 (b), 2013. Turbulence is mostly confined to the surface layer, but it deepened from z ~ 15 m on Nov 18 to z ~ 25 m on Nov 19.

Under moderate winds (speed W_a ~ 11-12 ms^{-1}), the surface low-salinity layer was effectively decoupled from the thermohalocline. Note the existence of horizontal/temporal gradients of T and S in the surface layer. Similar patterns were also observed on Nov 19 (Fig. 4b). Under higher winds, W_a ~ 16-18 ms^{-1}, the surface (homogeneous) mixed layer deepened only slightly, which continues to appear as decoupled from the pycnocline. The horizontal/temporal gradients of T, S, and σ_θ in the surface layer almost completely vanished because of enhanced wind stirring (Fig. 4b). To analyse changes to turbulence and stratification between Nov 18 and 19 in strongly salinity-stratified surface waters of BOB, individual profiles of T, S, σ_θ, N^2 and ε were calculated and are shown in Fig. 5 for the upper 30 meters.

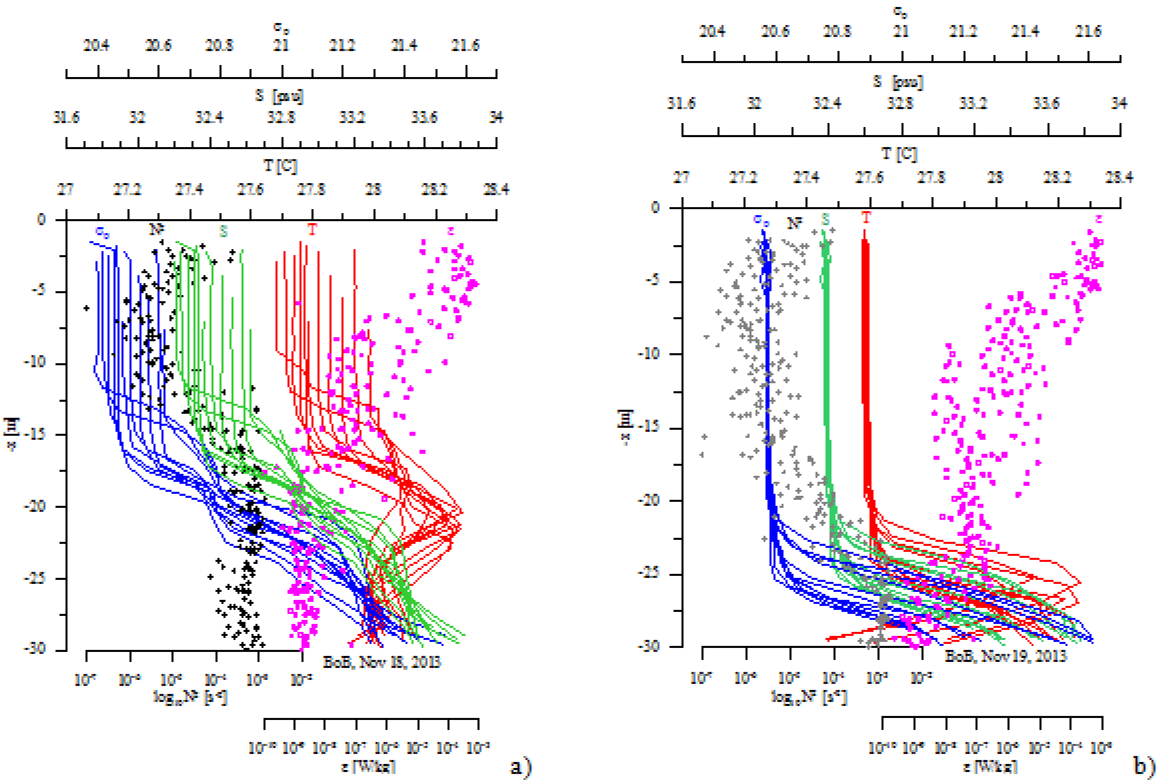

Figure 5. Vertical profiles of T (red), S (green), σ_θ (blue), $log_{10}N^2$(black) and ε (magenta) in the upper 30 m layer on Nov 18 (a) and Nov 19 (b).

On Nov 18, the upper boundary of the near-surface pycnocline was at z ~ 10 - 11 m, with the lower boundary at z ~ 15 m (see N^2 profiles in pane a). The turbulence intensity characterized by ε gradually decreased from ~ 3×10^{-5}– $\sim10^{-3}$ Wkg^{-1} at z = 5 m to $10^{-6}-10^{-8}$ Wkg^{-1} between z = 10 and z = 15 m, thereafter sharply decreasing to ε ~ 10^{-9} Wkg-^{1} and remaining approximately constant further down. The horizontal/temporal differences of T, S and σ_θ in the middle of the surface layer (z = 7 m) over a distance of ~ 2 km was $\Delta_x T\approx0.25$K, $\Delta_x S\approx0.4$ psu, and $\Delta_x\sigma_\theta\approx0.22$, respectively. The intensification of wind stress from ~ 0.16 Nm^{-2} on Nov 18 to ~ 0.5 Nm^{-2} on Nov 19 (not shown), led to an increase of $\varepsilon\approx10^{-6}-10^{-7}$ Wkg^{-1} across the entire mixing layer and to deepening of the homogeneous mixed layer to z ~ 22 m. This enhanced turbulence not only produced vertical mixing, but also initiated dramatic horizontal stirring, thus reducing the thermohaline differences, $\Delta_x T\approx0.017$ K, $\Delta_x S\approx0.02$ psu, and $\Delta_x\sigma_\theta\approx0.008$ over the same (~ 2.4 km) distance as before. A very strong pycnocline just below the surface mixed layer, however, suppressed wind-induced turbulence, precluding any penetration below z ~ 22 - 25 m. No internal sources of turbulence were evident in the water interior ($z\approx$ 22 - 120 m), suggesting that under mild and even relatively strong but ephemeral winds in the area before and on Nov 18-19, the surface layer and pycnocline were effectively detached from each other. Internal wave radiation and their breaking below the pycnocline appear to be damped, possibly by energy drainage due to local wave breaking in the pycnocline (where a slight increase of ε could be seen). Observations near the local frontal zones, however, were different.

A2. Surface-layer turbulence affected by a strong salinity front. Mesoscale lateral processes of the surface layer, characterized by filaments and lenses of diluted saline water, led to active frontogenesis, which, along with atmospheric forcing, strongly influenced turbulence and mixing in the upper layer. The VMP measurements across such a front observed on Nov 21 (two cross-sections with 6 and 8 casts, respectively) are shown in Fig. 6, where a very sharp "fresh water" front with a salinity change of > 1 psu over ~100 m is shown. This is one of the many fronts observed during R/V Roger Revelle cruises.

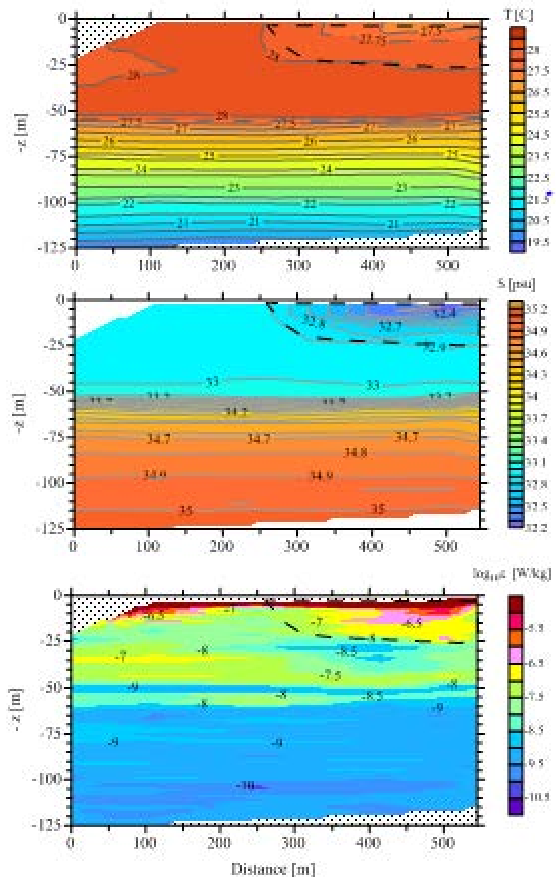

Figure 6. Temperature (upper), salinity (middle), and the dissipation rate (lower) panels across a sharp front in the upper 25 m layer. Nov 21, see Fig. 1.

This frontal feature was moving northward with a speed ~ 1 m/s, resembling a gravity current with a very turbulent core (compare the regions delimited by a dashed lines in the upper and lower panels of Fig. 6). Below the "fresh water" layer, turbulence is sharply sheltered, with ε reduced to less than 10^{-8} W/kg – blue region in the depth range 25-40 m. Turbulence in the region ~ 40 < z < 60 m (yellow-green strip in Fig. 6) has not been affected by the front, a result that requires further analysis. It appears the layers of stratification are isolated from each other, with little turbulent transport across them.

B. Thermohaline structure across the Sri Lanka Current. Salinity, temperature and potential density contour plots along the meridional (~ 80.4 E) and zonal (~ 8 N) sections taken across the Sri Lanka Current (Fig. 7a,b) show substantial differences in stratification between the southern and eastern branches of the current that reflect seasonal and spatial variability.

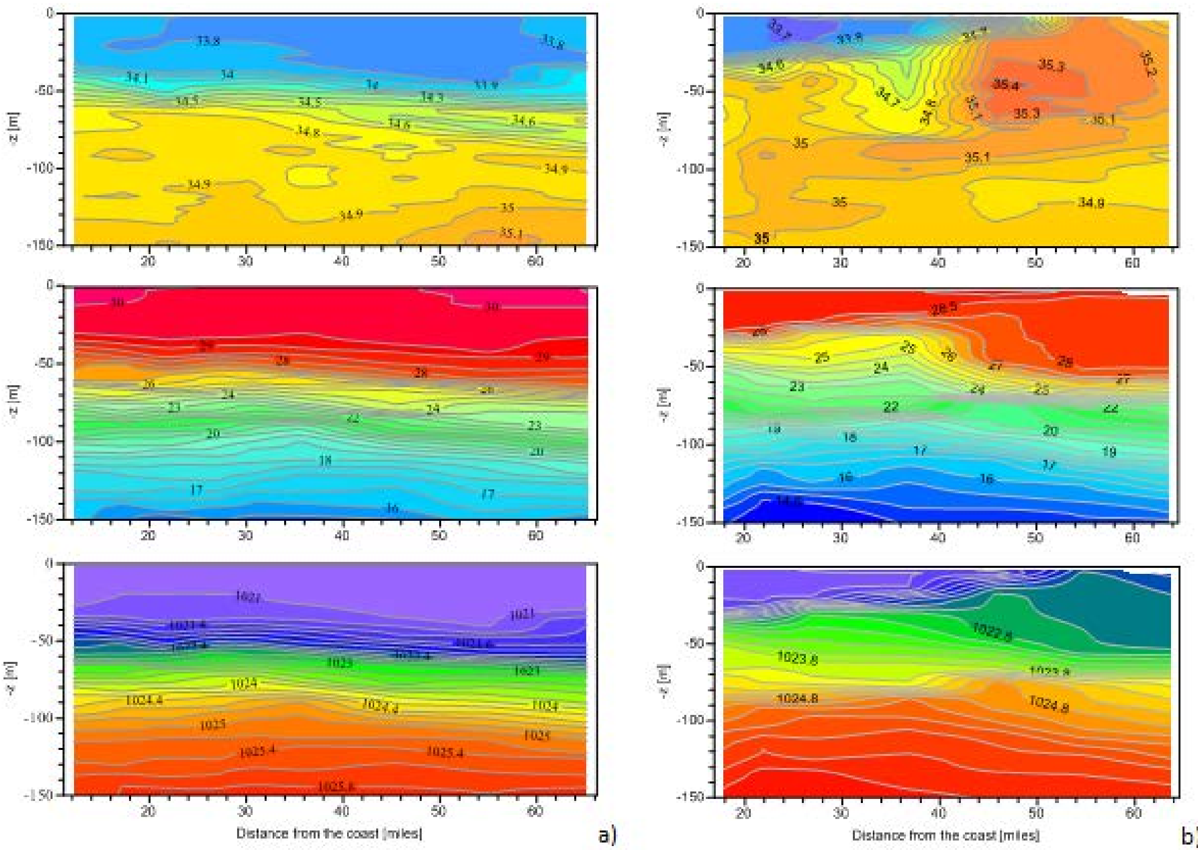

Figure 7. Contour plots of salinity (upper), temperature (middle), and potential density (lower) along longitudinal (a) and latitudinal (b) sections across the southern and eastern branches of Sri Lanka Current taken in April (left) and September (right), respectively.

During the inter-monsoon season (April, Fig.7a), the depth of the relatively well-mixed surface layer in blue water (> 12 miles from the coast) appears to be approximately constant (about 40 m) across the entire southern branch of the current. Lenses of slightly fresher and cooler water near the sea surface did not affect much of the near-surface density structure, as evidenced by a uniformly mixed upper layer and a sharp pycnocline. In general, the pycnocline became shallower toward the south, pointing to predominantly easterly geostrophic transport at the end of April. According to VMP measurements along the same section near the shelf break (Fig. 2a), the depth of the surface homogeneous layer in February is ~ 60 m, indicating the possibility of substantial convective cooling and/or strong wind mixing in the upper layer south of Sri Lanka during the winter monsoon.

On the contrary, toward the end of the summer monsoon, thermohaline structure across the eastern branch of Sri Lanka Current (Fig. 7b) is much more complex, exhibiting a sharp thermohalocline in the depth range z = 30-40 m near the shelf break. About 50 miles offshore, however, the pycnocline bends toward the sea surface, forming a striking thermohaline front that separates the diluted BOB surface water moving southward along the Sri Lanka coast from warm, saltier water at the eastern end of the transect (S_{max} > 35.4 psu at z = ~ 40 - 50 m, Fig. 7b) that may represent Arabian Sea water moving north and north eastward. The calculation of geostrophic velocities along the transect supports this notion. Further analysis of data from different transects is underway.

IMPACT/APPLICATION

The two research programs discussed involve international collaboration between scientists from the US, Sri Lanka, India, Seychelles, Singapore and Maldives (Pending). These two programs supports logistics of numerous US scientists operating in the Indian Ocean under ASIRI and NASCAR projects. Capacity building is a key component, and to this end we have hosted Mr. Priyantha Jinadasa (NARA) for the second time to complete his thesis work (April-July 2014). The Sri Lankan component of ASIRI helped to reach out to Seychelles and Maldives to initiate new collaboration that will allow future studies in the equatorial Indian Ocean, including studies on equatorial, east African, Mozambique/Mascarene and the Agulhas current systems.

RELATED PROJECTS

The PIs is working on an ONR 322-MMM funded project dealing with radio wave propagation in the marine boundary layer, where our role is intense experimentation and theoretical developments on coastal marine boundary layer (N 00244-14-2-0004).

PUBLICATIONS

Lucas, A., Shroyer, Emily, Wijesekera, Hemantha, Fernando, Harindra et al., From monsoons to mixing: the multi-scale mosaic of air-aea interactions in the Bay of Bengal, *Eos*, *Transactions American Geophysical Union,* **95 (30)**, 269-270.

Lozovatsky, I., S.U.P. Jinadasa, J.-H. Lee, H.J.S. Fernando. 2014. Internal waves in a summer pycnocline of the East China Sea. *Ocean Dynamics* (submitted)

Lozovatsky, I., S.U.P. Jinadasa, H.J.S. Fernando, J.-H. Lee, and C.-S. Hong. 2014. The wall-layer dynamics in a weakly-stratified tidal bottom boundary layer. *Continental Shelf Research* (submitted)

Lozovatsky, I., J.-H. Lee, H.J.S. Fernando, C.-S. Hong, and S.U.P. Jinadasa. 2014. Turbulence in the East China Sea: The summertime stratification. *Journal of Geophysical Research* (submitted).

Wijesekera, H. W., Jensen, T.G., Jarosz, E., Teague, W.J., Metzger, E.J., Wang, D.W., Jinadasa, U., Arulananthan, K., Centurioni, L., and Fernando, H.J.S., Southern Bay of Bengal currents and salinity intrusions during a fall monsoon transition, *Journal of Geophysical Research* (Submitted).

HONORS/AWARDS

The PI was awarded *Docteur Honoris Causa* by the Université Joseph Fourier (University of Grenoble), France, in March 2014.